

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

X-711-70-287  
PREPRINT

NASA TM X-63990

# FIELD AND PHOTON ENHANCED ELECTRON EMISSION CHARACTERISTICS OF CADMIUM SULPHIDE FIELD EMITTERS

AKRAM S. HUSAIN-ABIDI  
DONALD WALSH

JULY 1970



**GODDARD SPACE FLIGHT CENTER**  
GREENBELT, MARYLAND

FACILITY FORM 602

~~N70-34666~~

(ACCESSION NUMBER)

(THRU)

35  
(PAGES)

1  
(CODE)

TMX-63990

(NASA CR OR TMX OR AD NUMBER)

26

(CATEGORY)

FIELD AND PHOTON ENHANCED ELECTRON EMISSION  
CHARACTERISTICS OF CADMIUM SULPHIDE FIELD EMITTERS

Akram S. Husain-Abidi

Spacecraft Technology Division

And

D. Walsh

Department of Engineering Science

Parks Road, Oxford, England

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland

FIELD AND PHOTON ENHANCED ELECTRON EMISSION  
CHARACTERISTICS OF CADMIUM SULPHIDE FIELD EMITTERS

Akram S. Husain-Abidi

Spacecraft Technology Division

D. Walsh

Department of Engineering Science

Parks Road, Oxford, England

ABSTRACT

Preparation and electron emission characteristics of cadmium sulphide field emitters are described. Experimental results when plotted in accordance with Fowler-Nordheim theory were found to depart from linearity. The departure from linearity in low field region is ascribed to the surface electron states and in high field region due to electron phonon interactions. Work function was also calculated from Fowler-Nordheim plots and was found to be smaller than the one measured by photoelectric method. Photon enhanced emission has been observed by shining the laser light of photon energy equal to the energy gap in cadmium sulphide. The maximum enhanced emission current was as high as 14,000 times the dark field emission current, when the exciting light was parallel to the c-axis and illuminated the entire effective emitting area of the crystal. Under pulsed excitation and at higher incident photon densities (of the order of  $10^{18}$  photons/sec/cm<sup>2</sup>. or more), an additional component of shorter decay time appeared in the enhance emission. The transient characteristics are discussed in terms of recombination centers and trapping levels in cadmium sulphide.

## 1. INTRODUCTION

Field emission is a quantum mechanical phenomenon and was first reported by Wood<sup>1</sup> in 1897. Electron emission occurs by "tunnelling" through the deformed potential barriers encountered by the electrons at the surface of the material.

The magnitude of the field emission current depends upon:

- (A) the number of electrons from inside the semiconductor which arrive at unit area of the surface in unit time,
- (B) and the probability that an electron striking the surface will be emitted.

This probability is also termed as "transmission coefficient" of the surface, and is a function of electron energy and applied field.

It was thought that by illuminating the field emitter by laser light of some suitable wavelength whose quantum energy is less than the photoelectric threshold, the number of electrons from inside the semiconductor which arrive at unit area of the surface in unit time can be enhanced. The probability of tunneling through the barrier is a function of electron energy and therefore should be greater for conduction electrons that have absorbed light quanta. An increase in these two factors can result in an enhancement of field emission current.

Cadmium sulphide was chosen for experimental investigations mainly because of its energy gap. Since it is 2.4 eV, the two of the strong laser lines ( $\lambda = 4880 \text{ \AA}$  and  $5145 \text{ \AA}$ ) offers comparable quantum energies.

This paper describes some experiments carried out to observe the field and photon-enhanced field emission characteristics of cadmium sulphide single crystals.

## 2. EXPERIMENTAL DETAILS

All crystals used in our experiments were "pure" in the sense that no impurities were deliberately added during growth. The dark resistivity was of the order of  $10^7$  Ohms/cm., and the mobility determined by Hall effect measurements was in the range of 130 to 200  $\text{cm}^2/\text{V. sec.}$  The crystals were cut in rectangular bars  $0.5 \times 0.5 \times 10$  mm. The long dimension was along the c-axis. One end of each bar was then mechanically tapered into a cone with a typical half angle of  $15^\circ$ .

The crystal was then attached (by an Ohmic contact) to the tungsten arc of a Müller type field emission microscope tube's stem. The Ohmic contact techniques have been described by Shulman<sup>2</sup>, and Boer<sup>3</sup>. The latter technique was preferred because the crystal can be outgassed by vacuum heat treatment without affecting the electrical properties of the contact.

The conical crystal was further sharpened by chemically etching it in a drop of hydrochloric acid suspended on a tungsten wire loop. The temperature of the acid was varied between  $35^\circ$  to  $55^\circ\text{C}$  by heating the wire loop. As the tip thinned down the concentration of acid was correspondingly reduced. After achieving a reasonably sharp conical point, the emitter was electropolished by using a capacitor discharge technique in a solution of hydrochloric acid. During this process the emitter was kept under very strong illumination. After electropolishing the emitter was thoroughly washed in distilled water and immediately mounted in an electron microscope tube.

The field emission microscope tube was then evacuated. The vacuum system included a 25 litres/sec. triode ion pump and a titanium pump of about 2,500 cm<sup>2</sup> effective surface. Baking facilities were provided for temperatures up to 350°C. After meticulous evacuation, a final pressure of the order of  $10^{-10}$  torr was achieved. The field emitter was then outgassed by electron bombardment. This also sharpened the emitter tip, apparently by preferential evaporation. Laser skiographical measurements showed that the half angle of the emitter shank was 6° and the tip radius about  $5 \times 10^{-5}$  cm.

The tube was then sealed off from the main pumping system and the ultra high vacuum was maintained by a Mullard IOG 12 ion gauge. To study the photon enhanced field emission current, light from both continuously working (C. W.), and pulsed argon ion lasers was used to excite the field emitters. The pulsed laser was operated in 1.5 microsecond duration pulses at a repetition rate of 50 per second. Facilities for selecting individual laser lines were provided by using a quartz prism in the laser cavity. The laser output power was controlled by varying the discharge current of the laser tube and by neutral density filters. For photon enhanced emission studies the use of the conventional Müller type field emission microscope tube was avoided as it was thought that the green fluorescence of the willemite screen might affect the experimental results. In the new emission tube molybdenum was used as an anode and facilities were provided for cooling the tip to liquid nitrogen temperature and shining the laser light on to the tip from two different directions. Figure 1 shows the schematic diagram of the experimental arrangements.

### 3. EXPERIMENTS AND RESULTS

#### (i) Current-voltage characteristics of cadmium sulphide field emitters.

Initially, when the voltage was applied, the current was very unsteady and there were rapid variations in the intensity of the small bright spots flickering on the willemite screen. By applying high voltage pulses and leaving the emission for several hours these patterns were stabilized. The final patterns were fairly similar to those reported by us in an earlier publication<sup>4</sup>.

Having achieved a satisfactory field emission pattern the emitter was then removed from the microscope tube and was placed in a diode type structure. This eliminated the complicating effects of green fluorescence of the willemite screen on the photoconductivity of cadmium sulphide. All experiments for studying the current-voltage characteristics were carried out in total darkness.

Figure 2 shows two typical plots at room and liquid nitrogen temperatures. The current is plotted logarithmically against the reciprocal of the applied voltage in accordance with the Fowler-Nordheim equation. It can be seen from the Fig. 2 that the curve is fairly linear at least for four decades of current. The non-linearity in the low field region can be explained in terms of the influence of surface electron states. As Stratton<sup>5</sup> has pointed out these surface states reduce the penetration of an external field into a semiconductor, consequently causing a smaller field emission current.

The non-linearity in the high field region is associated with a relative reduction in the field emission current. In our experiments this occurs for current

densities greater than  $5 \times 10^4 \text{ A/cm}^2$ . This can be ascribed to a number of phenomenon such as a drop in the voltage at the emitter during the passage of the field emission current through it, (this means a reduction in  $\log I$  compared with the linear law), interband field emission in Cadmium Sulphide and current saturation due to electron-phonon interactions in the strong field. While it is possible that all these phenomena will be affecting the field emission current, the most dominant is the latter phenomenon.

In the strong electric field region, the current saturation and ultrasonic amplification phenomena in Cadmium Sulphide crystals have been the subject of much work. The critical phenomenon is that of current saturation occurring when the drift velocity of electrons exceeds a certain critical value nearly equal to the velocity of sound. The work of Hutson, McFee and White<sup>6</sup>, Smith<sup>7</sup>, and McFee<sup>8</sup> has suggested that the pronounced saturation effects in Cadmium Sulphide is due to the interaction of the drifting carriers with the piezoelectric modes of lattice vibrations. A detailed account of electron-phonon interaction in strong fields and current saturation has been reported by Yamashita et. al.<sup>9</sup> and Isida et.al.<sup>10</sup>,

(ii) Determination of work function from Fowler-Nordheim plots and the comparison of the experimental results with the computed values

Experimental results, although confirming the theoretical emission laws qualitatively, gave inexplicable values for the work function. All these experiments were performed in total darkness. The work function calculated from the

slopes of Fowler-Nordheim plots was found to vary between 1.37 to 2.58 eV. Field emitters cooled at liquid nitrogen temperature (77°K) have shown no significant change in the work function values. All these values were found to be smaller than those measured by the photoelectric method, (which are normally between 4.1 to 4.8 eV).

Experimental results were also compared with the computed values of the Fowler-Nordheim equation, (modified by Stratton<sup>5</sup> for semi-conductors to take into account the image force and field penetration corrections). Current densities were computed by successive approximations of work function for applied fields ranging between  $10^6$  to  $10^7$  V/cm. These were then compared with the experimental values. Figure (3) shows the semi-logarithmic plot of current density  $J$  as a function of applied field  $F$  for a work function of 1.5 eV. The solid line in Fig. 3 corresponds to the experimental values. Considering the assumptions involved regarding the field emitter geometry, the theoretical and experimental values seem to be in fairly good agreement.

### (iii) Effects on threshold voltage upon laser excitation

The first noticeable effect of laser excitation was the reduction in threshold voltage of the field emission current. What we mean by threshold voltage is that voltage at which a current of the order of  $10^{-10}$  amperes appears in the circuit. More than 25 field emitters were examined and in all experiments the threshold voltage was found to be reduced. The 5154 Å wavelength laser line was used for excitation and as the intensity of the laser light was increased the threshold

voltage was found to move towards lower voltages. This can be seen from the Fowler-Nordheim plots of Fig. 4.

(iv) Excitation by C. W. argon ion laser

To measure the photon enhanced emission, the experiments were started by first evaluating the current-voltage characteristics of field emitters in total darkness. After each experiment the performance of the field emitter was re-examined to find whether the results were reproducible. Only those crystals with reproducible current voltage characteristics were used to study the photon enhanced field emission phenomenon.

In one set of experiments the laser power incident upon field emitter was kept constant and the current-voltage characteristics was measured. A number of other experiments were performed by increasing the laser power in steps. Figure 4 shows the Fowler-Nordheim plots of one of the field emitters under dark and various illumination conditions. This experiment was performed at room temperature and the 5145 Å laser line was used for excitation. The incident laser beam was perpendicular to the c-axis of the crystal and illuminated approximately half of the effective emitting area of the field emitter. It can be seen from the Fig. 4 that the current rose as the power of the incident illumination was increased. It can also be seen that each of the characteristics shows a complex dependence of  $\log I$  on  $I/V$ .

In general the following observations were found to be common for all field emitters:

- (a) at low excitation intensities, (up to  $10^{14}$  photons/sec./cm.<sup>2</sup>) the Fowler-Nordheim plots were fairly linear. Deviations from linearity was observed at higher photon flux.
- (b) the rise in enhanced emission current was critically dependent upon the illumination, and
- (c) the rise in enhanced emission current was much faster at higher laser power than at low powers.
- (v) Excitation by Pulsed Argon Ion Laser

The laser pulse was of 1.5 microsecond duration with a repetition rate of 50 per second. In most of the experiments the two laser wavelengths used to excite the field emitter were 4880 Å and 5145 Å. The photon energies corresponding to these wavelengths are 2.54 and 2.41 eV. To study the transient characteristics of photon enhanced emission the following four experiments were carried out:

1. To study the pulsed photon enhanced field emission current and its transient characteristics, the laser beam was focused on to the entire effective emitting area of the field emitter. The incident photon density was approximately  $10^{18}$  photons/sec./cm.<sup>2</sup>. The most dominating laser lines in the pulsed argon ion laser beam were 5145 Å, 4965 Å and 4880 Å. Prior to laser excitation the voltage was set to give a field

emission current of  $10^{-7}$  amperes. Upon laser excitation this current rose to about 1.4 milliamperes (peak current), approximately 14,000 times higher than its dark emission current. Also the enhanced emission current lasted much longer than the exciting laser light pulse, as can clearly be seen from the Figure 5a.

As regards the transient characteristics of this enhanced current, there are two distinct decay regions in Figure 5a. The first is a fast one with a time constant of approximately  $350 \times 10^{-6}$  seconds and the second is a much slower region with a time constant of about  $7 \times 10^{-3}$  seconds, (the time constant is the time for the photo current to decay to half its original value). The initiation of the current pulse follows very closely the laser pulse. The peak enhanced current lasted for about  $15 \times 10^{-6}$  seconds and after that it decays to the second step in another  $10^{-3}$  seconds. After this stage there was a very slow decay during the rest of the  $1.8 \times 10^{-2}$  seconds before the arrival of the second laser pulse.

Figure (6) shows the dependence of the peak enhanced emission current of short lived component  $\Delta I_s$ , and the peak amplitude of its long lived component  $\Delta I_L$  on the intensity of the laser light. It can be seen that there is a sharp transition to saturation in the slow decay region. The peak of fast decay component continues to rise with the laser light.

An analysis of the nature of decay current will be given in the next section.

2. This experiment was performed to study the effect of 5145 Å laser line excitation and the decay characteristic of enhanced emission current. Figure (5b) shows an oscilloscope trace of enhanced emission current pulse. The peak enhanced emission current was approximately 0.21 milliamperes, about 2,100 times greater than that of its dark emission current value. As in the previous experiment there are two distinct decay regions. The fast component has a time constant of approximately 200 microseconds, 150 microseconds smaller than in the previous case. The rate of decay was found to be reduced considerably after about one millisecond and there was very slow decay during the rest of the  $2 \times 10^{-2}$  seconds.

To study the type of slow decay of photon enhanced field emission current, the logarithm of enhanced emission current in the slow decay region  $\Delta I_L$ , was plotted against time,  $t$ . This is shown in Fig. (7) and it can be seen that the decay is exponential.

When the intensity of the incident light in the above experiment was reduced by a factor of 5, the peak enhanced emission current was found to be reduced by a factor of 4. Also the decay rate was not as fast as in the previous experiment. The time constant of the fast decay component was approximately 400 microseconds, 200 microseconds faster than its previous value. This is shown in the oscilloscope trace of Fig. (5c).

3. The effect of cooling the tip to liquid nitrogen temperature (77°K) is illustrated in Fig. (8a, b). The peak enhanced emission currents were  $1.7 \times 10^{-4}$  and  $5 \times 10^{-5}$  amperes respectively. Besides a decrease in peak enhanced field emission current from the peak current value at room temperature, the current decay times were longer. In this experiment the decrease in peak enhanced emission was about 67% after two milliseconds compared to a decrease of about 35% after the same time in the experiment when the field emitter was at room temperature. Again the 5145 Å laser line was used for excitation. When the intensity was reduced by a factor of 5 the peak enhanced emission current was found to be reduced by a factor of 3.6, this is illustrated in Fig. (8b). The bottom trace of both Figs. (8a, and b) are the base lines that indicate zero field emission current. The second straight lines show the magnitude of d.c. field emission current and the top pulses are the enhanced field emission current. Both sets of results were taken when the laser light was perpendicular to the c-axis of the crystal and roughly illuminated half of the effective emitting area of the tip.
4. To study the general behaviour of the pulsed photon enhanced field emission current, the logarithm of peak current was plotted against the inverse of the applied voltage, (same as in the Fowler-Nordheim plots). The field emitter was at room temperature and the peak power of the 5145 Å wavelength laser line was 5 watts. The curve at the top,

in the Fig.(9) shows the peak enhanced emission current while the curve at the bottom shows the plot when the field emitter was in total darkness.

#### IV. DISCUSSION OF RESULTS

##### (i) Enhanced Emission Mechanism.

The photon enhanced field emission cannot be explained simply by the photoconductive effect in Cadmium Sulphide as the latter is much less field dependent. Possibilities of photoelectric field emission from emitters can also be excluded as our measurements, as well as Shauba's<sup>11</sup>, have shown that photoelectric emission from Cadmium Sulphide occurs only in the far ultra violet. (The measured quantum yield was only  $5 \times 10^{-8}$  at  $h\nu = 5$  eV). Therefore it is almost certain that the photon enhanced emission occurs by electron tunneling through the surface barrier after being excited by photons of quantum energy equal to or very close to the band gap of Cadmium Sulphide. The photon excitation increases the number of electrons from inside the semiconductor which arrive at unit area of the surface in unit time, thereby increasing the magnitude of the field emission current.

The enhanced emission was also observed for incident photon energies up to about 0.1 eV less than the energy gap in Cadmium Sulphide, i.e., the 5145 Å laser line. Shallow trapping levels just below the edge of the conduction band may be responsible for this phenomenon. In the presence of these levels the enhanced emission will be a two step process. Absorption of incident photon of some suitable quantum energy will excite additional electrons into empty shallow levels from where they will be field excited.

The transition probability,  $D$ , for field excitation from shallow levels was computed for electric fields normally encountered during the field emission process. The following expression of Franz<sup>12</sup> was used:

$$D = \exp \left[ - \frac{4}{3} \{ (2m^*)^{1/2} / h e F \} \Delta E^{3/2} \right].$$

where

$F$  = electric field in v/cm.

$h$  = Planck's constant

$m^*$  = effective mass

$e$  = electronic charge

and

$\Delta E$  = the trap depth in eV.

The values of  $D$  for depths of levels ranging from 0.02 to 0.1 eV are tabulated in Table 1. It can be seen from this table that for the majority of the applied fields the transition probability approaches unity. The high transition probability of field excitation from shallow trapping levels, together with the long free carrier life time in Cadmium Sulphide ( $10^{-2}$  to  $10^{-4}$  seconds), seem to be responsible for the observed enhancement in field emission current.

## (ii) Deviation of Fowler-Nordheim plots.

One interesting phenomenon is the deviation from linearity of the Fowler-Nordheim plots in the high field region (Fig. 4 and 9). Unlike the deviation of these plots in total darkness, the non-linearity under photon excitation is

associated with a relative increase in the field emission current. This was also true when the peaks of the pulsed photon enhanced emission currents were plotted logarithmically against the reciprocal of the applied voltage, as can be seen in Fig. (9) (curve 3). This phenomenon can be interpreted in terms of electric field induced absorption, as was predicted by Franz<sup>12</sup>.

(iii) Laser Heating Effects.

Laser induced thermionic emission was also considered. The heat transfer equation predicts a temperature rise

$$T = \frac{2 \alpha P_0}{\rho \kappa C_p} \sqrt{t}$$

where  $\alpha$ ,  $P_0$  and  $t$  are the absorption coefficient, laser power density, duration of the laser pulse and  $\rho$ ,  $\kappa$ ,  $C_p$  are the density, thermal conductivity and specific heat of the material respectively. Under the experimental conditions employed for Cadmium Sulphide:

$$\alpha = 0.4$$

$$P_0 = 10 \text{ watt/cm}$$

$$t = 10^{-6} \text{ seconds}$$

$$\rho = 4.82 \text{ g/cm}^3$$

$$\kappa = 0.2 \text{ w/cm/}^\circ\text{C.}$$

$$C_p = 0.226 \text{ J/gm/}^\circ\text{C.}$$

This gives a predicted temperature rise,  $T = 7 \times 10^{-3} \text{ }^\circ\text{C}$ , is far too small to produce any significant thermionic effect.

#### (iv) Transient Characteristics of Enhanced Emission

The photon enhanced emission observed by exciting the field emitters with one microsecond duration pulses of laser light, ( $\lambda = 4880 \text{ \AA}$  and  $5145 \text{ \AA}$ ) lasted more than 20 milliseconds. In our experimental arrangement, when the number of photons arriving at the field emitters was of the order of  $10^{18}$  photons/sec/cm<sup>2</sup> or more, an additional component of shorter decay time appeared in the enhanced emission. This transient emission can be explained in terms of recombination centres with different cross-sections for capture of electrons and holes. The fundamental features of recombination in materials like Cadmium Sulphide have been defined by Bube<sup>13</sup> and Rose<sup>14</sup>. A simplified model for a system of recombination levels is shown in Fig.(10). Suppose there are two types of recombination levels  $N_{r1}$  and  $N_{r2}$ . The levels  $N_{r1}$  have a large capture cross-section for holes\* but a small one for electrons. The levels  $N_{r2}$  have a small capture cross-section for holes but a large one for electrons, so that

$$N_{r2} S_{p2} \ll N_{r1} S_{p1}$$

( $S_p$  being the hole capture cross-section).

Because of this relation at low excitation intensities the levels  $N_{r2}$  do not take any significant part in the recombination process, (they do not capture holes). Upon increasing the excitation intensity the  $N_{r1}$  levels capture more and more photoholes until they are completely filled. Consequently, the photocurrent decay becomes saturated. This is in agreement with the experimental results as can be seen from the dependence on the intensity of the light pulse of the peak amplitude of the photon enhanced field emission current of the long lived component  $\Delta I_L$ , Fig. (6).

A further increase in excitation intensity will generate more electron hole pairs and the recombination centres  $N_{r2}$  will begin to capture the excess holes. This will cause an instantaneous recombination with electrons and will be observed as a fast decay component. Figure (5a) is a typical example of this process.

## V. CONCLUSIONS

A satisfactory method for preparing field emitters of Cadmium Sulphide crystals has been developed. In the high field region when the current density exceeds to  $5 \times 10^4$  Amps/cm<sup>2</sup>, the field emission current becomes non-linear. This current saturation is ascribed to the electron phonon interaction in Cadmium Sulphide.

Photon enhanced field emission current was also observed. Experimental results have shown that photon enhanced field emission current is due to the electron tunneling through the deformed surface barrier after being excited by photons of quantum energy equal to very close to the band gap of Cadmium Sulphide. The pulsed photon enhanced emission current shows the characteristic recombination processes of electrons and holes in Cadmium Sulphide.

The ultra high sensitivity and instantaneous photon enhanced emission of electrons suggests that they can be used as efficient narrow band photon detectors.

## ACKNOWLEDGMENTS

The authors wish to express their thanks to Drs. H. Metz and J. K. L. Cranstoun for valuable discussion and Dr. R. W. C. Gray for his assistance. It is also a pleasure to thank D. Schaefer for his support and encouragement.

## REFERENCES

1. R. W. Wood, Phys. Rev. 5, 1., (1897).
2. C. J. Shulman, Phys. Rev. 98, 384, (1955).
3. K. W. Boër, and R. B. Hall, J. Appl. Phys. 37, 4739, (1966).
4. S. A. Husain and D. Walsh, Electronic Letters, 2, 440 (1966).
5. R. Stratton, Proc. Phys. Soc. (London) B68, 746, (1955).
6. A. R. Hutson, J. H. McFee and D. L. White, Phys. Rev. Letters 7, 237, (1961).
7. R. W. Smith, Phys. Rev. Letters 9, 87, (1962).
8. J. H. McFee, J. Appl. Phys. 34, 1548, (1963).
9. J. Yamashita and K. Nakamura, Proc. of the International Conference of Semiconductors, Kyoto J. of Phys. Soc. Japan (Supplement) 21, 455, (1966).
10. A. Ishida, C. Hamaguchi, and Y. Inuishi, J. of the Phys. Soc. Japan (Supplement), 21, 469, (1966).
11. I. A. Shauba, Zh. Tekh. Fiz. 26, 1129, (1956).
12. W. Franz Annln. Phys. 11, 17, (1952).
13. K. Bube, "Photoconductivity of Solids", (John Wiley & Sons), (1960).
14. A. Rose, "Concepts in Photoconductivity and allied problem", (John Wiley & Sons), (1963).

TABLE I

Applied Field 10 <sup>6</sup> V/meters	DEPTH OF LEVELS (eV)			
	$\Delta E = .02$	$\Delta E = .04$	$\Delta E = .05$	$\Delta E = .1$
1	0.908	0.761	0.683	0.340
10	0.990	0.973	0.963	0.898
20	0.995	0.986	0.981	0.947
30	0.997	0.991	0.987	0.965
40	0.998	0.993	0.990	0.973

TABLE I

Applied Field $10^8$ V/meters	DEPTH OF LEVELS (eV)			
	$\Delta E = .02$	$\Delta E = .04$	$\Delta E = .05$	$\Delta E = .1$
1	0.908	0.761	0.683	0.340
10	0.990	0.973	0.963	0.898
20	0.995	0.986	0.981	0.947
30	0.997	0.991	0.987	0.965
40	0.998	0.993	0.990	0.973

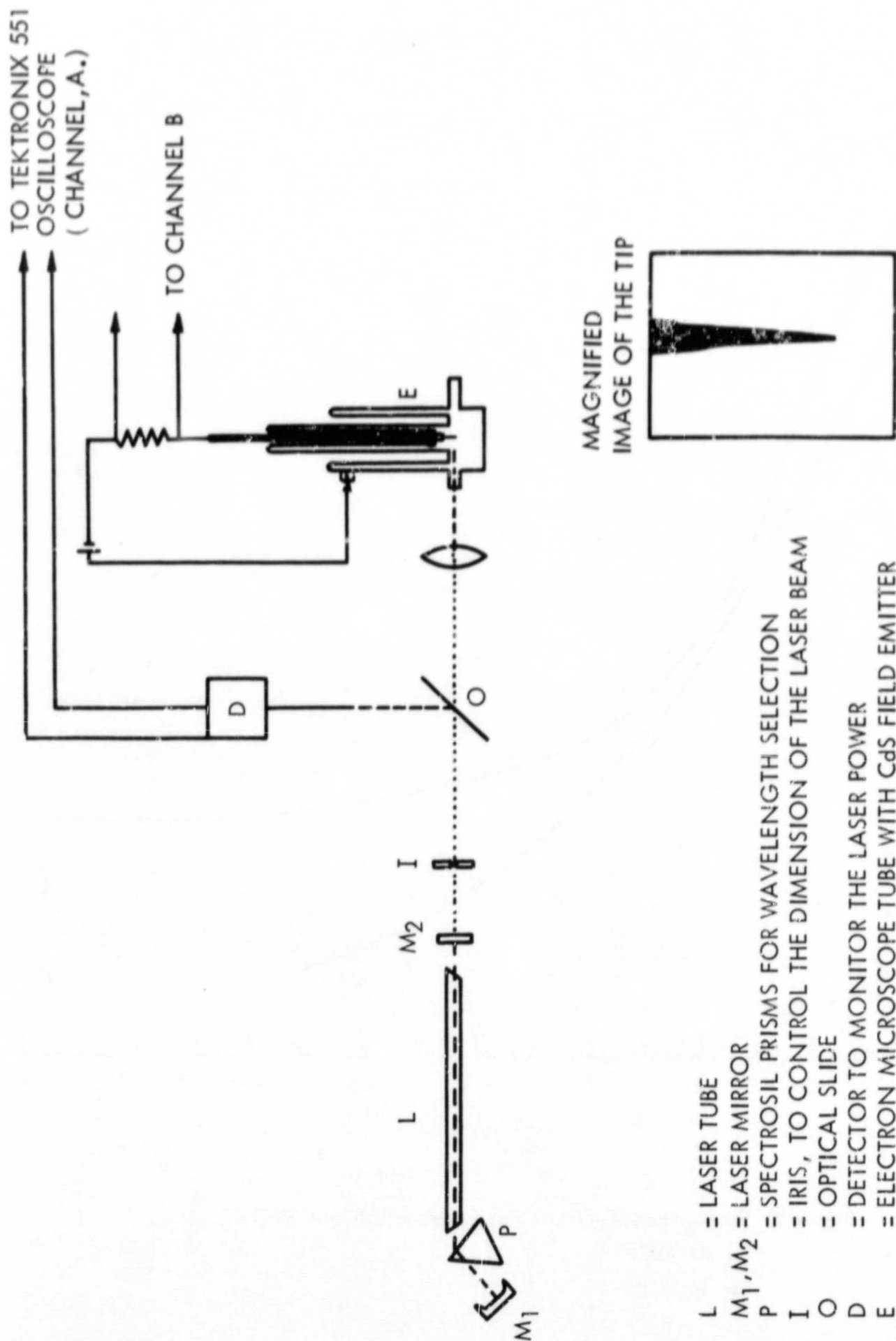


Figure 1. Schematic Diagram of the Experimental Set Up

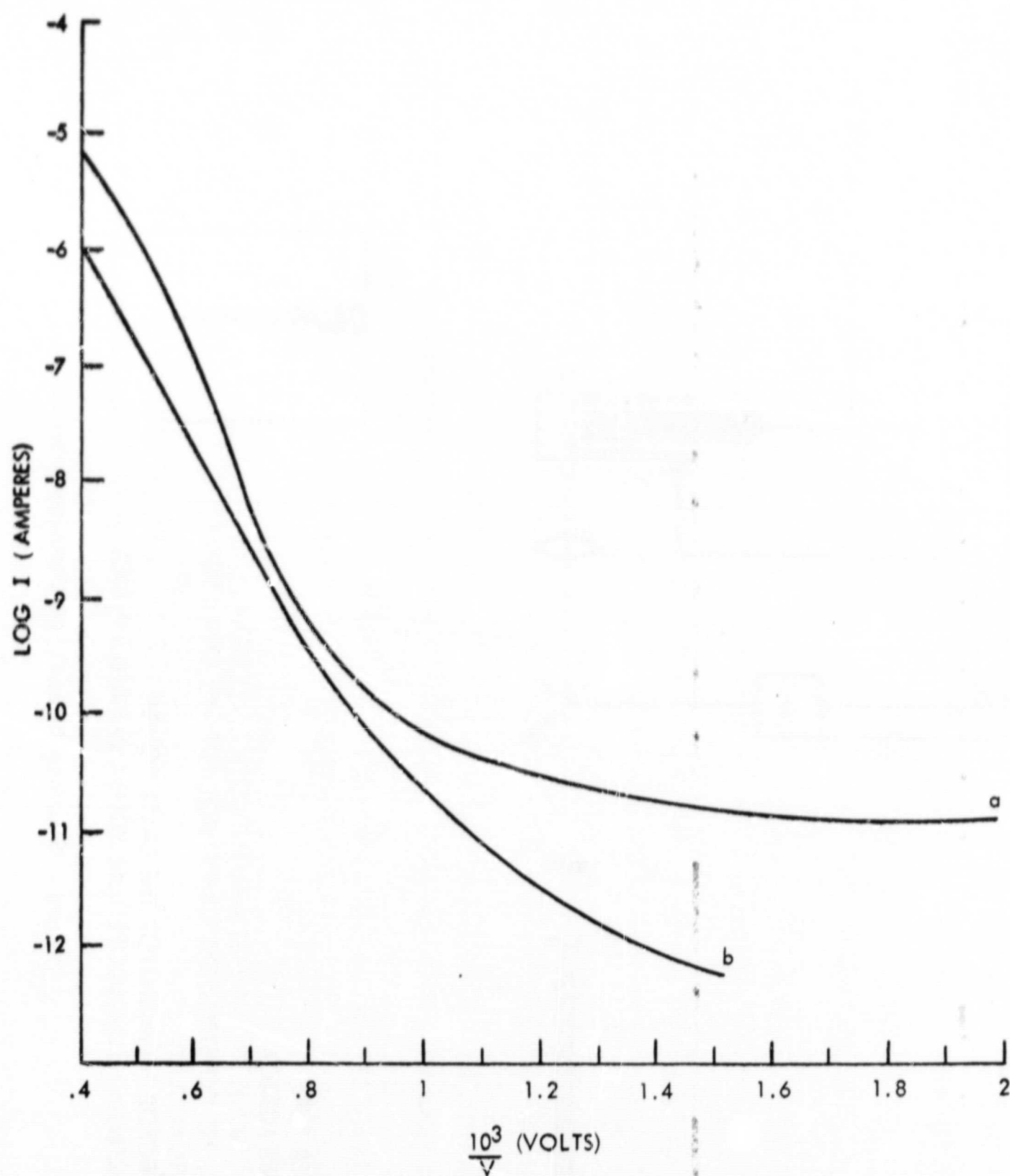


Figure 2. Fowler-Nordheim Plots For Cadmium Sulphide Single Crystals

(a) At 300°K

(b) At 77°K

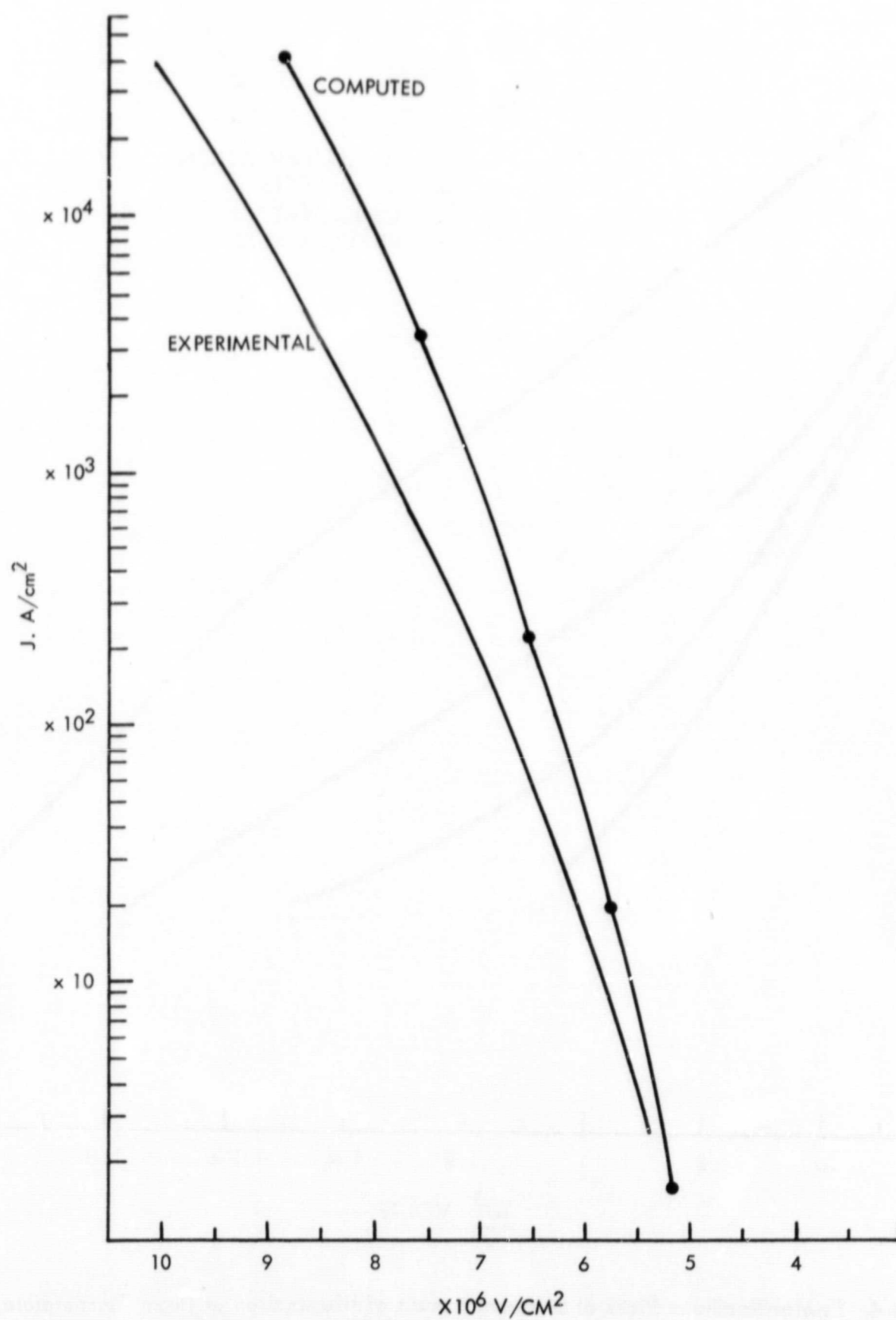


Figure 3. Comparison Between Computed and Experimental Values of Current Densities For a Given Applied Field  
(Solid Line Experimental Values)  
(Dotted Line Computed Values)

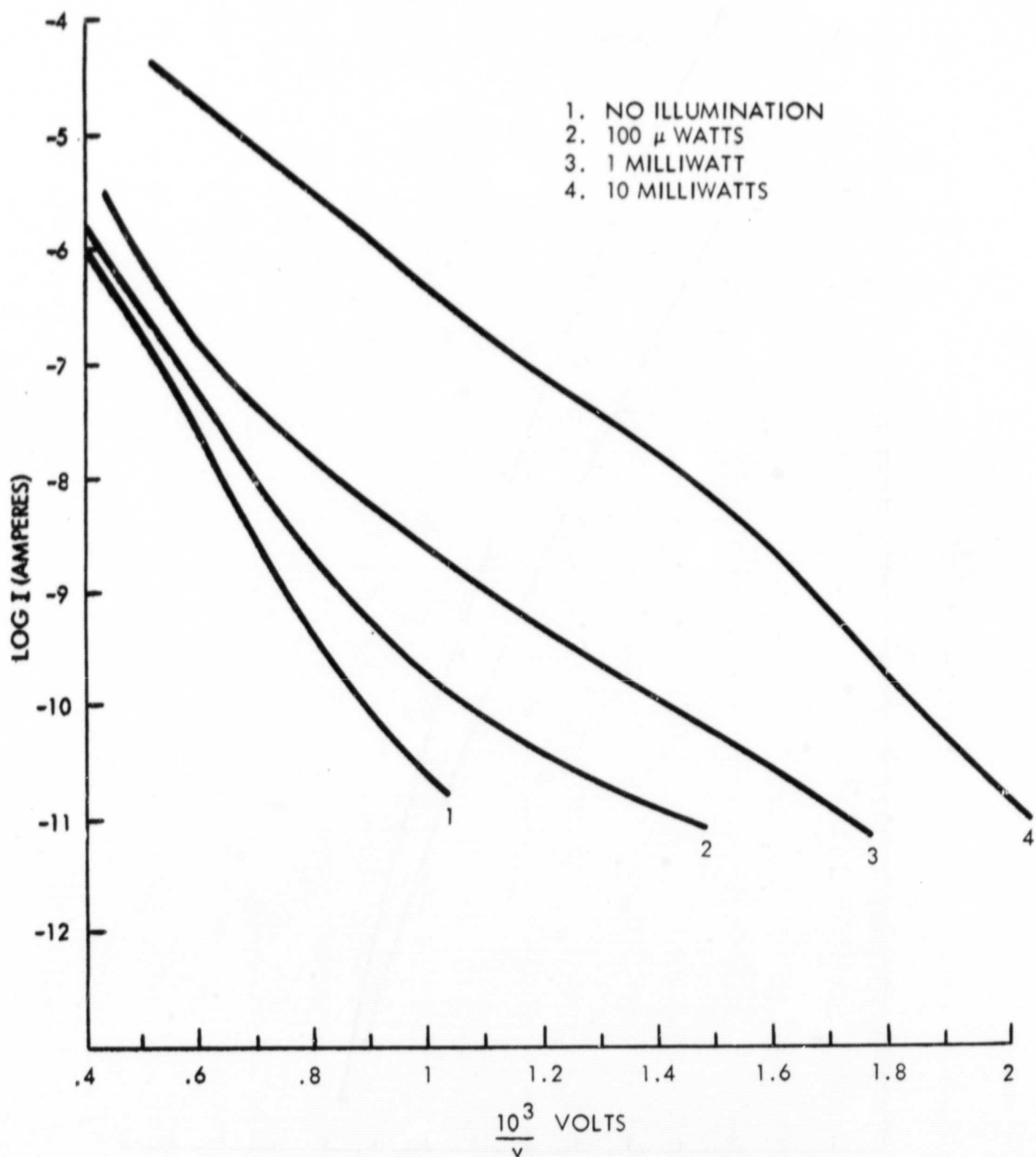
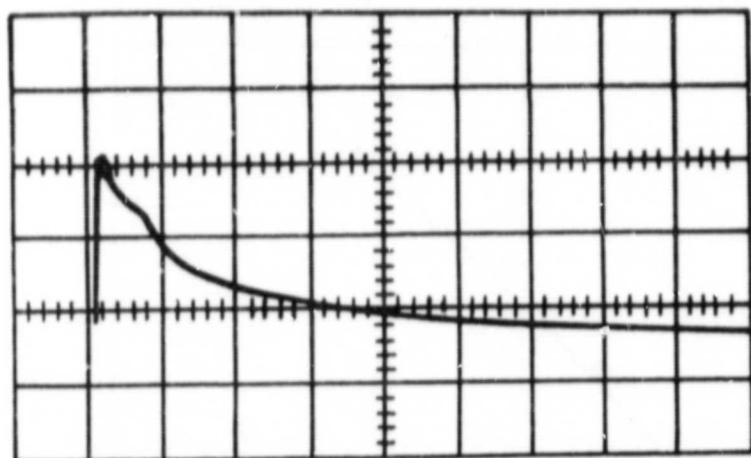


Figure 4. Fowler-Nordheim Plots at Different Levels of Illumination at Room Temperature When excited by 5145 Å Laser Light



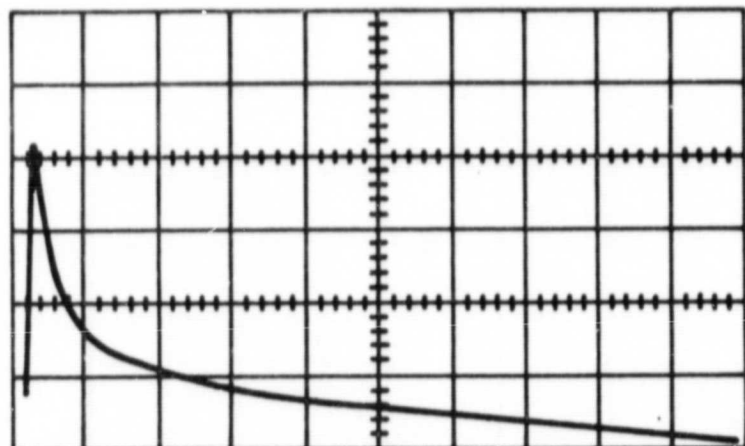
(a)

Figure 5(a)

A Typical Laser-Induced Emission Pulse, With All Argon Lines. Field Emitter Excited With Light Parallel to c-Axis of the Cds Crystal (at Room Temperature).

Horizontal Scale = 2 ms Per Division

Vertical Scale = 0.5 mA Per Division



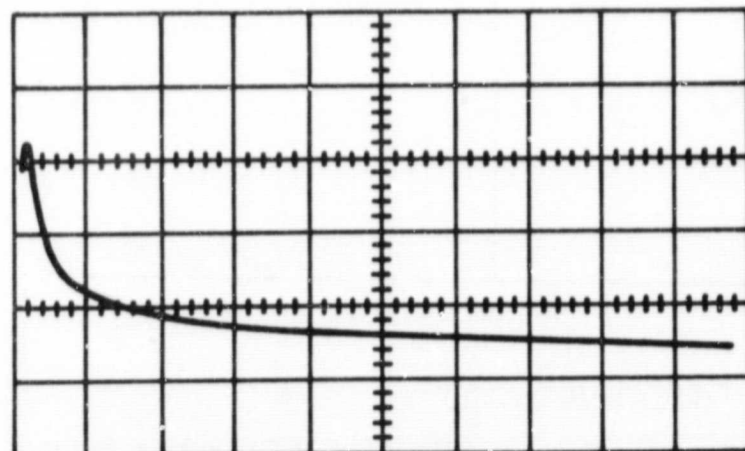
(b)

Figure 5(b)

Photon Enhanced Field Emission Current Pulse With Light Perpendicular to c-Axis of Crystal, at Room Temperature With Only 5145 Å Line.

Horizontal Scale = 2 ms Per Division

Vertical Scale = 0.05 mA Per Division



(c)

Figure 5(c)

Emission Pulse When the Laser Intensity Was Reduced by a Factor of 5 From (b).

Horizontal Scale = 2 ms Per Division

Vertical Scale = 0.02 mA Per Division

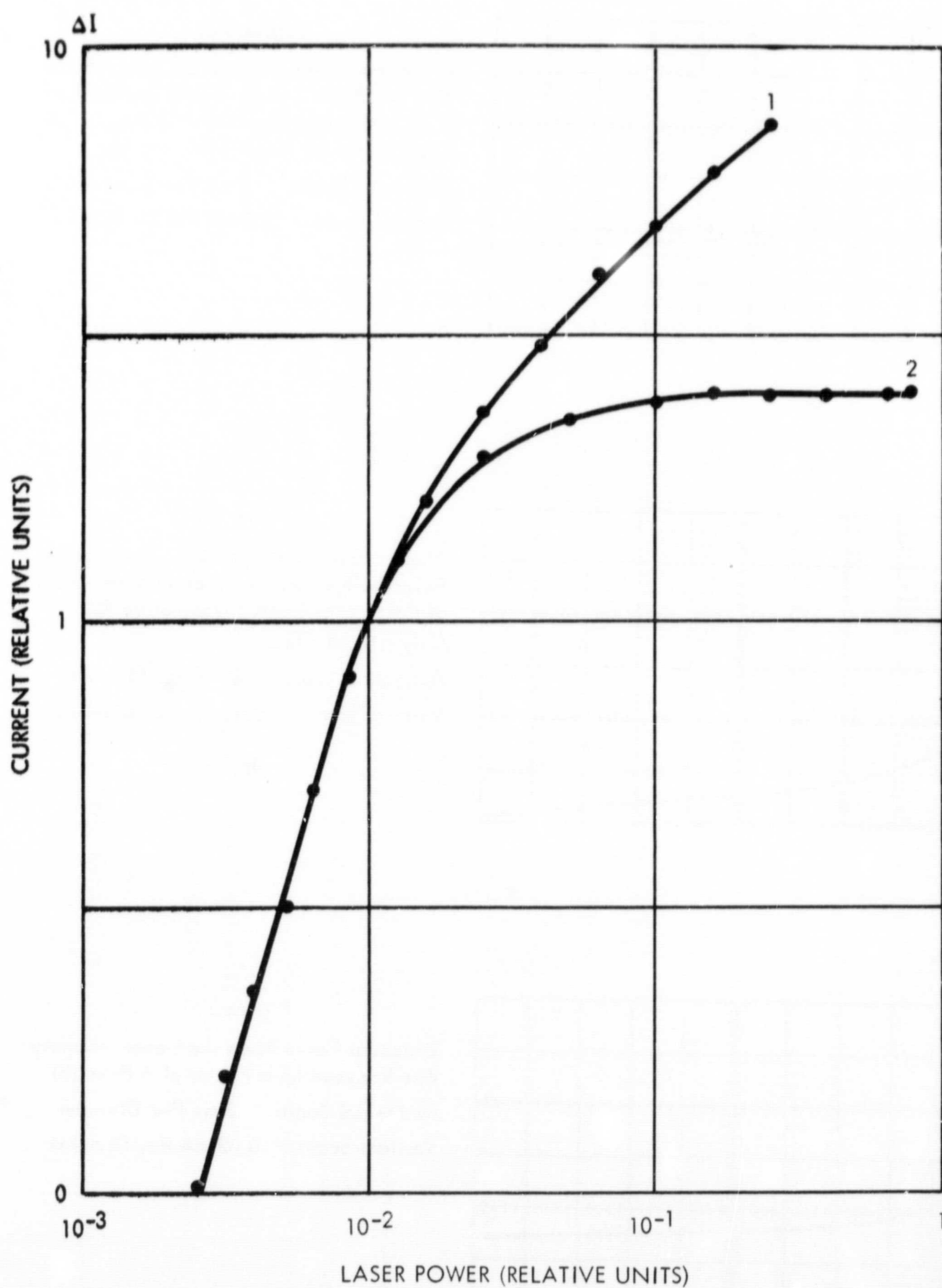


Figure 6. Dependence of the Peak Enhanced Emission Current of Short-Lived Component  $\Delta I_s$  and the Peak Amplitude of its Long-Lived Component  $\Delta I_L$  on the Laser Power

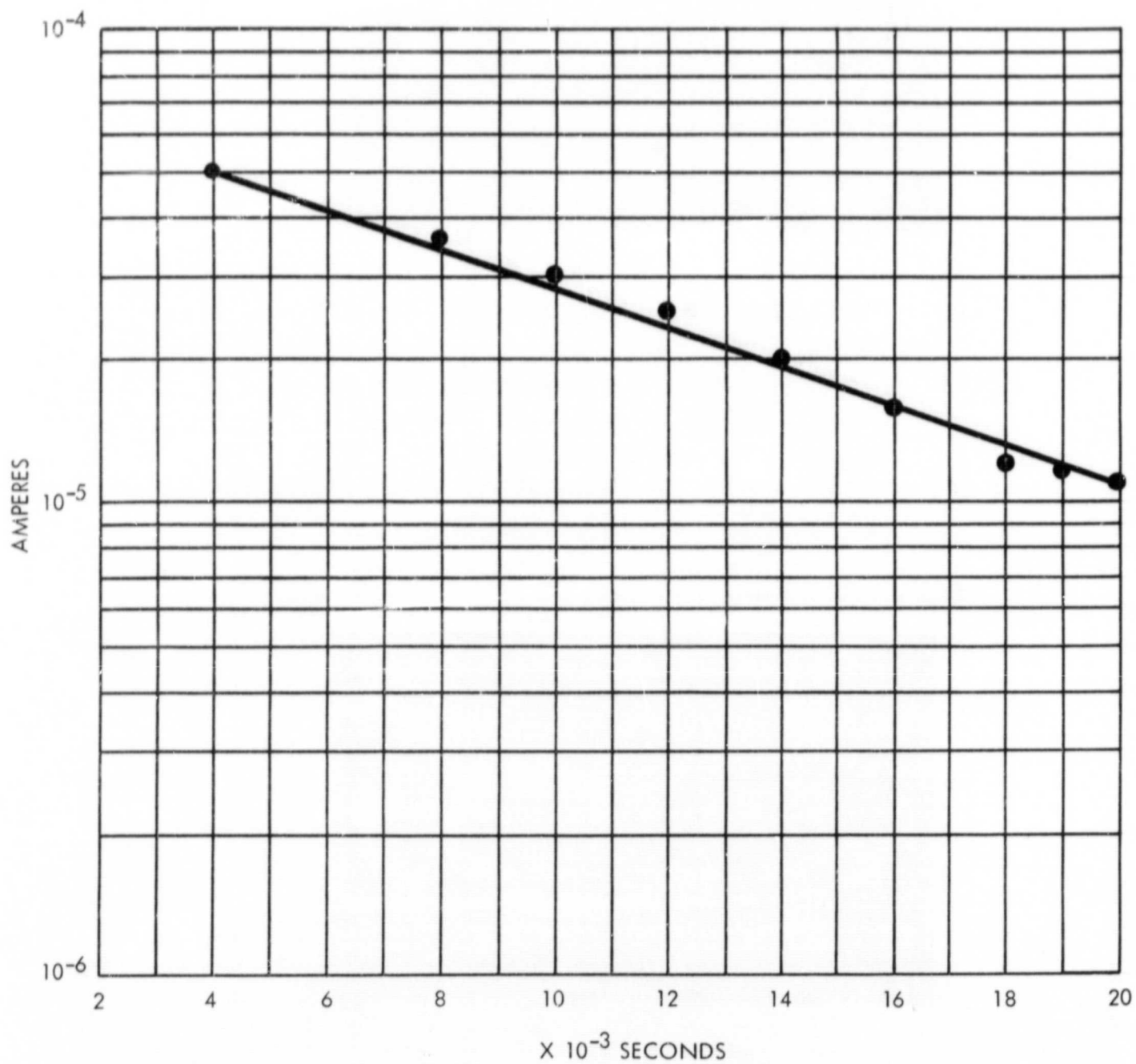
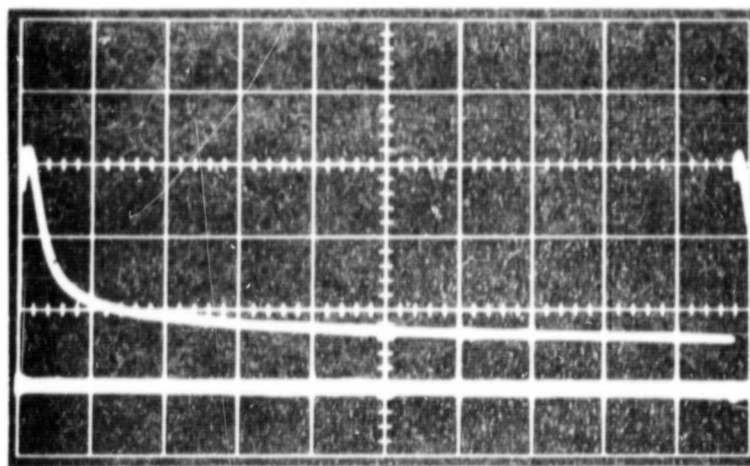


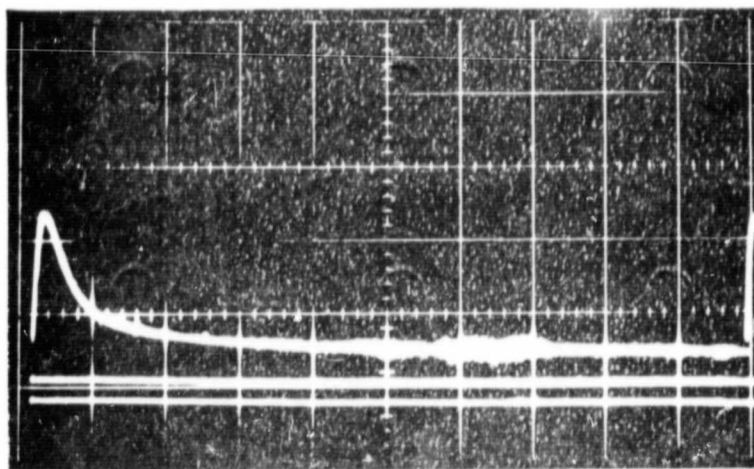
Figure 7. Slow Decay Region in the Coordinates  $\text{Log}(\Delta I_L, t)$  Where  $\Delta I_L$  Is the Enhanced Emission Current in Slow Decay Region and  $t$  the Time



(a)

- ( i ) FIRST BASELINE INDICATES WHEN THERE IS NO FIELD EMISSION.
- ( ii ) SECOND LINE INDICATES EMISSION AT DIRECT APPLIED VOLTAGE; VERTICAL SCALE =  $0.5 \mu\text{A}$  PER DIVISION.
- ( iii ) LASER-INDUCED CURRENT PULSE; HORIZONTAL SCALE =  $0.05 \text{ mA}$  PER DIVISION.

Figure 8(a). Emission Pulse at Liquid Nitrogen Temperature



(b)

- ( i ) FIRST LINE: BASELINE.
- ( ii ) SECOND LINE: FIELD EMISSION AT DIRECT APPLIED VOLTAGE; VERTICAL SCALE =  $0.5 \mu\text{A}$  PER DIVISION.
- ( iii ) LASER-INDUCED PULSE; HORIZONTAL SCALE =  $2 \text{ ms}$  PER DIVISION, VERTICAL SCALE =  $0.02 \text{ mA}$  PER DIVISION.

Figure 8(b). Emission Pulse When Laser Intensity Was Reduced by a Factor of 5

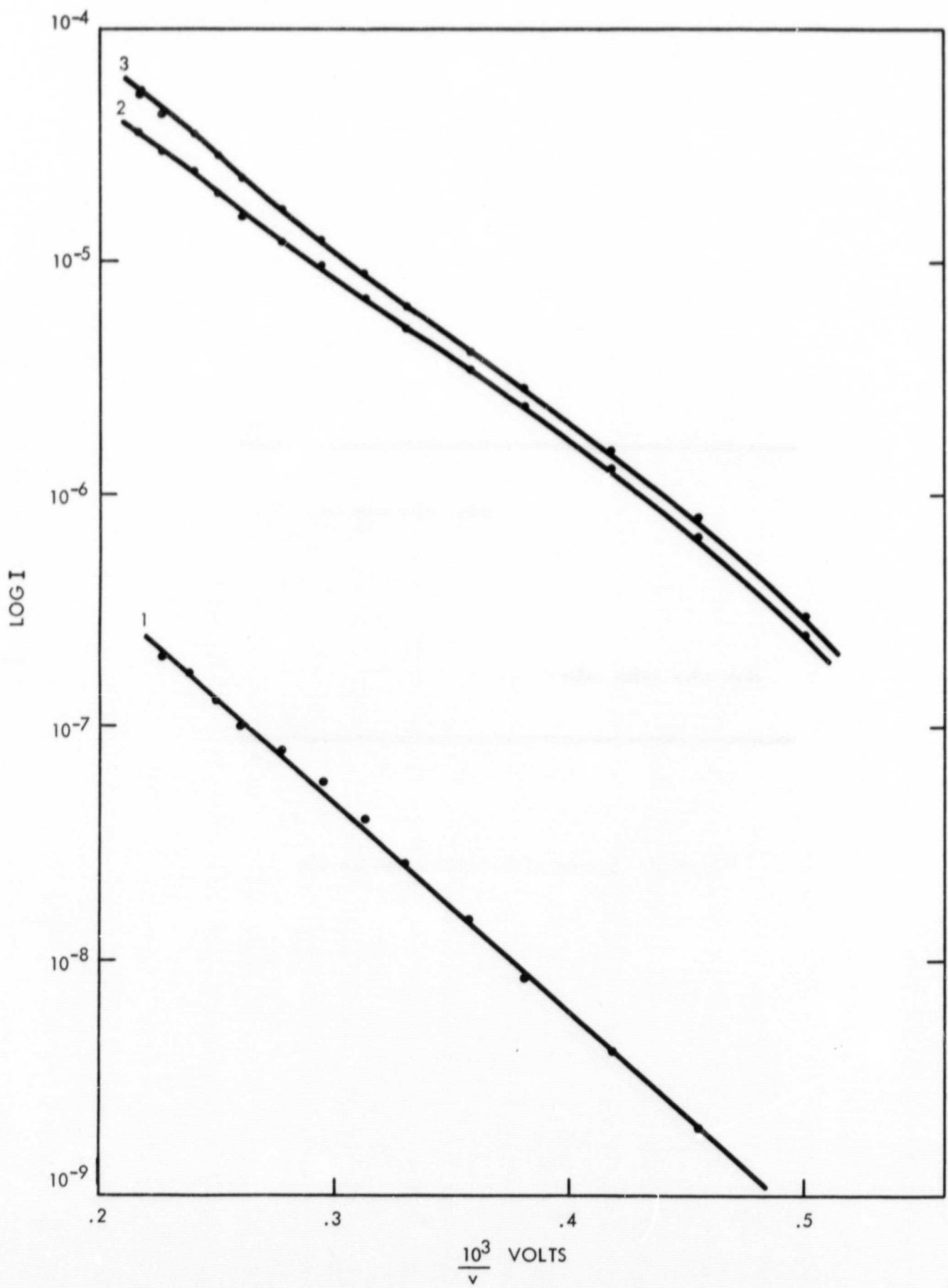


Figure 9. Fowler-Nordheim Plot in Dark and Under Pulsed Excitation  
 Excitation Wavelength 5145 Å — Peak Laser Power 5 Watts

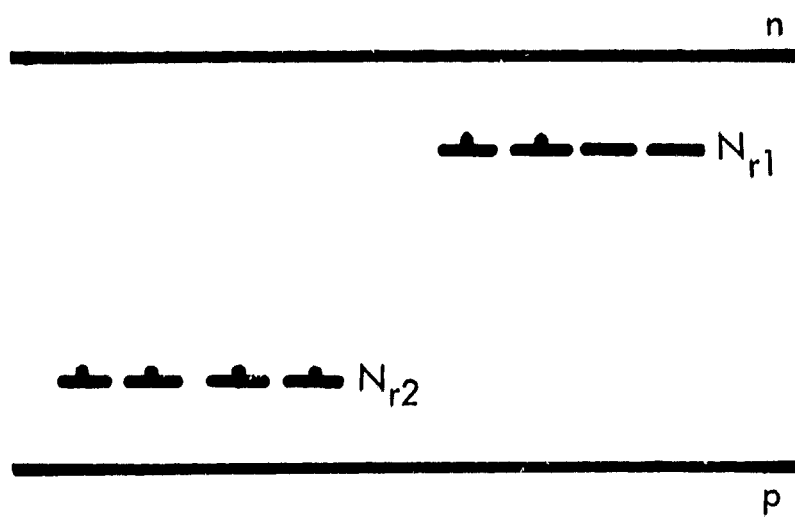


Figure 10. System of Recombination Levels

## FIGURE CAPTIONS

Figure 1. Schematic diagram of the experimental set up.

- L = Laser tube
- $M_1$  &  $M_2$  = Laser mirrors
- P = Spectrosil prism for wavelength selection
- I = Iris, to control the dimension of the laser beam
- O = Optical slide
- D = Detector to monitor the laser power
- E = Electron microscope tube with CdS field emitter.

Figure 2. Fowler-Nordheim plots for Cadmium Sulphide single crystals.

(a) at 300°K

(b) at 77°K

Figure 3. Comparison between computed and experimental values of current densities for a given applied field.

(solid line experimental values)

(dotted line computed values)

Figure 4. Fowler-Nordheim plots at different levels of illumination at room temperature when excited by 5145 Å laser light.

1 = no illumination

2. 100μ watts

3. 1 milliwatt

4. 10 milliwatts.

- Figure 5(a).** A typical laser-induced emission pulse, with all argon lines.  
Field emitter excited with light parallel to c-axis of the Cds crystal (at room temperature).  
Horizontal scale = 2 ms per division  
Vertical scale = 0.5 mA per division.
- Figure 5(b).** Photon enhanced field emission current pulse with light perpendicular to c-axis of crystal, at room temperature with only 5145 Å line.  
Horizontal scale = 2 ms per division  
Vertical scale = 0.05 mA per division.
- Figure 5(c).** Emission pulse when the laser intensity was reduced by a factor of 5 from (b).  
Horizontal scale = 2 ms per division  
Vertical scale = 0.02 mA per division.
- Figure 6.** Dependence of the peak enhanced emission current of short-lived component  $\Delta I_s$  and the peak amplitude of its long-lived component  $\Delta I_L$  on the laser power.
- Figure 7.** Slow decay region in the coordinates  $\log (\Delta I_L, t)$  where  $\Delta I_L$  is the enhanced emission current in slow decay region and  $t$  the time.
- Figure 8(a).** Emission pulse at liquid nitrogen temperature
- (i) First baseline indicates when there is no field emission current.
  - (ii) Second line indicates emission at d.c. applied voltage,
- Vertical scale: 0.05  $\mu$ A per division.

(iii) Laser-induced current pulse

Horizontal scale = 2 ms per division

Vertical scale = 0.05 mA per division.

Figure 8(b). Emission pulse when laser intensity was reduced by a factor of 5.

(i) First line: baseline, indicates no field emission current.

(ii) Second line: field emission current at d.c. applied voltage.

Vertical scale:  $0.5 \mu\text{A}$  per division.

(iii) Laser induced pulse

Horizontal scale: 2 ms per division

Vertical scale: 0.02 mA per division.

Figure 9. Fowler-Nordheim plot in dark and under pulsed excitation.

Excitation wavelength  $5145 \text{ \AA}$

Peak laser power 5 watts.

Figure 10. System of recombination levels.